Baryon Spectroscopy and the Origin of Mass

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Abstract. The proton mass arises from spontaneous breaking of chiral symmetry and the formation of constituent quarks. Their dynamics cannot be tested by proton tomography but only by studying excited baryons. However, the number of excited baryons is much smaller than expected within quark models; even worse, the existence of many known states has been challenged in a recent analysis which includes - compared to older analyses - high-precision data from meson factories. Hence πN elastic scattering data do not provide a well-founded starting point of any phenomenological analysis of the baryon excitation spectrum. Photoproduction experiments now start to fill in this hole. Often, they confirm the old findings and even suggest a few new states. These results encourage attempts to compare the pattern of observed baryon resonances with predictions from quark models, from models generating baryons dynamically from meson-nucleon scattering amplitudes, from models based on gravitational theories, and with the conjecture that chiral symmetry may be restored at high excitation energies. Best agreement is found with a simple mass formula derived within AdS/QCD. Consequences for our understanding of QCD are discussed as well as experiments which may help to decide on the validity of models.

INTRODUCTION

Baryon spectroscopy is at a bifurcation point. The Particle Data Group [1] lists 44 N and Δ resonances which stem mostly from the old analyses of the Karlsruhe-Helsinki (KH) [2] and Carnegie-Mellon (CM) [3]collaborations. The most recent analysis of the SAID group at George Washington University (GWU) [4] includes high precision data from meson factories and data with measurements of the proton recoil polarization. So we should expect the number of known states to increase. Instead, SAID finds 20 only. This is a much smaller number than the 72 known mesonic states, not to speak about the wealth of additional states revealed from the QMC-St-Petersburg analysis of Crystal-Barrel LEAR data. Of course, a much greater number of states is expected for (three-body) baryons than for (two-body) mesons. Here, we will address the question wether we have to abandon a large fraction of baryon resonances listed by the PDG or if we should include them when interpreting the data in models.

The most natural and most popular frame to discuss baryon resonances is the quark model. But other concepts have been proposed. Here, data will be compared to quark-model predictions, to the Skyrme model, to AdS/QCD. At the end, I will address a few key issues in theory and will propose key experiments, which may help to decide on the validity of the different concepts.

WHY BARYON SPECTROSCOPY?

We all have an intuitive knowledge of what "mass" means. But, as often in physics, Nature offers surprises. Astronomers believe that only a small fraction of the total mass of the Universe is matter in the form as we know it. Close galaxies seem to drift apart faster than more remote galaxies (Fig. 1, left); the acceleration is assigned to a mythic dark energy (accounting for 73% of the mass of the Universe). The rotational frequencies of stars in galaxies do not depend on the distance from the galaxy center (Fig. 1, center); dark matter, e.g. in the form of super-symmetric particles, is introduced which gives a 23% mass contribution. "Normal" matter makes up the remaining 4%. The myriads of stars in the nightly heaven constitute just 1% of the total mass (Fig. 1, right).

The matter as we know it provides surprises for us as well. We are accustomed to the fact that electrons carry only an atomic mass fraction of 1/4000; their binding energy is in the sub-ppm range. In nucleons, it is the field energy which outcasts the quark mass by a factor hundred. 99% of the baryon mass does not come of the quark

FIGURE 1. *Left: The Hubble constant is larger for close-by galaxies. Center: The velocities of stars within galaxies does not depend on their distance to the center. Right: Mass distribution.*

masses but from chiral symmetry breaking. The small current quark mass due to the quark-Higgs interaction is not very important on the hadronic scale.

The fundamental theory of strong interactions, QCD, is chirally invariant, it keeps handiness, for the nearly massless quarks. This symmetry is dynamically broken, giving to quarks an effective mass. This effect can be studied in lattice gauge calculations [5] which show an increase in mass with decreasing momentum transfer (see Fig. 2). At small q, the effective mass is about 320 MeV. This is called the constituent quark mass. It can be understood using different languages. The bag model assigns the constituent quark mass to absence of quark condensates inside of the bag [6]; the Dyson Schwinger equation approximates the effective gluon operator [7]; quarks hop between special field configurations called instantons by flipping the quark spin and thus, these acquire mass [8]. How can we learn about constituent quarks? Certainly not by deep inelastic scattering. Proton

Figure 2. *The quark mass as a function of the momentum transfer [5]*

tomography reveals the distribution of linear and orbital angular momenta but information on collective degrees of freedom is lost. The wave length with which the proton is explored needs to match the size of the constituents. This is the realm of spectroscopy.
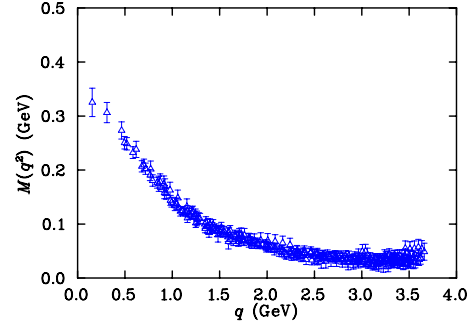
EXPERIMENTAL STATUS

The Particle Data Group [1] lists 44 nucleon and Δ resonances, Table 1 presents a recent compilation [9]. Evidence for the existence of baryon resonances is derived mostly from elastic πN scattering. Depending on the confidence with which their existence and their properties are known, these resonances are decorated with one, two, three or four stars. Except for the four-star resonances, the evidence is challenged by a careful GWU analysis [4] and only those boldfaced in Table 1 survive. Spin and parity of resonances are given in the form $N_{1/2^-}(1535)$ which gives spin and parity directly instead of $N(1535)S_{11}$ used by the Particle Data Group.

Table 1. *N and Δ resonances. Compilation: see [9]. ^{a}: BnGa; ^{b}: GWU.*

Resonance	Mass	Resonance	Mass	Resonance	Mass
$N(\mathbf{940})$	940	$\Delta(\mathbf{1232})$	1232 ± 1	$N_{\mathbf{1/2^+}}(\mathbf{1440})$	1450 ± 32
$N_{\mathbf{1/2^-}}(\mathbf{1535})$	1538 ± 10	$N_{\mathbf{3/2^-}}(\mathbf{1520})$	1522 ± 4	$N_{\mathbf{1/2^-}}(\mathbf{1650})$	1660 ± 18
$N_{3/2^-}(1700)$	1725 ± 50	$N_{\mathbf{5/2^-}}(\mathbf{1675})$	1675 ± 5	$\Delta_{\mathbf{1/2^-}}(\mathbf{1620})$	1626 ± 23
$\Delta_{\mathbf{3/2^-}}(\mathbf{1700})$	1720 ± 50	$\Delta_{3/2^+}(1600)$	1615 ± 80	$N_{\mathbf{3/2^+}}(\mathbf{1720})$	1730 ± 30
$N_{\mathbf{5/2^+}}(\mathbf{1680})$	1683 ± 3	$N_{1/2^+}(1710)$	1713 ± 12	$\Delta_{1/2^+}(1750)$	
$N_{1/2^-}(1905)$	1905 ± 50	$N_{3/2^-}(1860)$	1850 ± 40	$N_{1/2^+}(1880)^a$	
$N_{3/2^+}(1900)^a$		$N_{5/2^+}(1910)$	1880 ± 40	$N_{7/2^+}(1990)$	2020 ± 60
$\Delta_{1/2^-}(1900)$	1910 ± 50	$\Delta_{3/2^-}(1940)$	1995 ± 60	$\Delta_{\mathbf{5/2^-}}(\mathbf{1930})$	1930 ± 30
$\Delta_{\mathbf{1/2^+}}(\mathbf{1910})$	1935 ± 90	$\Delta_{3/2^+}(1920)$	1950 ± 70	$\Delta_{\mathbf{5/2^+}}(\mathbf{1905})$	1885 ± 25
$\Delta_{\mathbf{7/2^+}}(\mathbf{1950})$	1930 ± 16	$N_{1/2^+}(2100)$	2090 ± 100	$N_{1/2^-}(2090)$	
$N_{3/2^-}(2080)$	2100 ± 55	$N_{5/2^-}(2060)^a$	2065 ± 25	$\mathbf{N_{7/2^-}}(\mathbf{2190})$	2150 ± 30
$N_{5/2^-}(2200)$	2160 ± 85	$\mathbf{N_{9/2^-}}(\mathbf{2250})$	2255 ± 55	$\Delta_{1/2^-}(2150)$	
$\Delta_{\mathbf{5/2^-}}(\mathbf{2223})^{\mathbf{b}}$		$\Delta_{7/2^-}(2200)$	2230 ± 50	$N_{\mathbf{9/2^+}}(\mathbf{2220})$	2360 ± 125
$\Delta_{7/2^+}(2390)$	2390 ± 100	$\Delta_{9/2^+}(2300)$	2360 ± 125	$\Delta_{\mathbf{11/2^+}}(\mathbf{2420})$	2462 ± 120
$\Delta_{9/2^-}(2400)$	2400 ± 190	$\Delta_{3/2^-}(2350)$	2310 ± 85	$N_{11/2^-}(2600)$	2630 ± 120
$N_{13/2^+}(2800)$	2800 ± 160	$\Delta_{13/2^-}(2750)$	2720 ± 100	$\Delta_{15/2^+}(2950)$	2920 ± 100

For an interpretation of the resonance spectrum it is decisive to know if we need to abandon the 24 states not seen by SAID. At present, we cannot decide if the KH and CM analyses pick up some noise or if resonances are lost in the GWU analysis by the applied smoothing procedure. But for a few resonances, seen in the KH and CM analyses and not seen in the GWU analysis of elastic πN scattering data, this question can be studied. We give three examples where resonances found by KH and CM and disclaimed by GWU are required in inelastic reactions. Note that the relevant $\pi N \to \pi N$ amplitudes [4] are included in the fit. KH, CM, and GWU fit only these amplitudes; the inelasticity is unconstrained by data. In the BnGa analysis, most inelastic channels are known from photoproduction and only few inelastic channels (mainly with vector mesons) are treated as "black box".

The $\Delta_{3/2^+}(1600)$ from $\pi^+ p \to \Sigma^+ K^+$:
Fig. 3 shows the imaginary part of the elastic P_{33} πN scattering amplitude above $\Delta(1232)$. Points (in red) with error bars represent the GWU amplitude, the thin (red) line a BnGa fit. The $\Delta(1232)$ tail is followed by a continuum; there is no evidence for further structures. The KH amplitude is represented by black triangles; the dominant $\Delta(1232)$ tail is removed. The amplitude exhibits a peak in the imaginary part, evidencing a $\Delta_{3/2^+}$ resonance at 1600 MeV coupling to πN. The CM partial wave agrees with KH in exhibiting a peak structure. The question is which analysis is correct the old analyses by CM and KH finding $\Delta_{3/2^+}(1600)$ or GWU where the resonance does not exist. The amplitudes derived from elastic πN scattering are ambiguous. The BnGa fit includes data on the inelastic reaction $\pi^+ p \to \Sigma^+ K^+$. Due to the charge, intermediate resonances must have isospin $I = 3/2$. The data were included in a general fit to a large number

Figure 3. *The P_{33} amplitude.*

of different inelastic reactions and to the GWU elastic amplitudes. The resulting P_{33} amplitude is shown as thick (blue) curve. The amplitude follows closely the KH amplitude. The analysis requires to introduce $\Delta_{3/2^+}(1600)$. The need for the resonance can be seen from the differential distribution and the induced Σ^+ polarization. Thus we believe that the $\Delta_{3/2^+}(1600)$ is definitely confirmed with a pole position at $M = 1540^{+40}_{-80}$, $\Gamma = 230 \pm 40$ MeV.
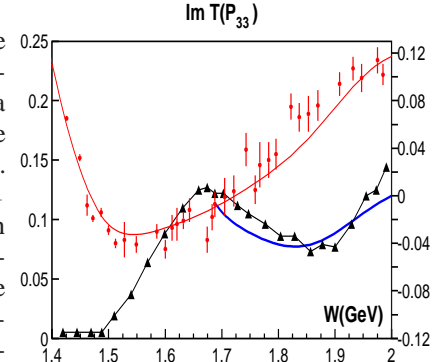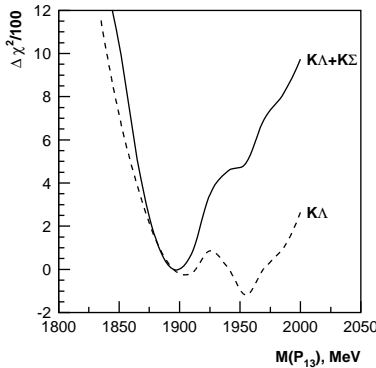

Figure 4. *χ^2 as a function of the imposed $N_{3/2^+}(1900)$ mass.*

The $N_{3/2^+}(1900)$ from photoproduction of hyperons:
Very sensitive data on photoproduction of hyperons are now available on $\gamma p \to \Lambda K^+$, $\gamma p \to \Sigma^0 K^+$, and $\gamma p \to \Sigma^+ K^0$. Fig. 4 shows the χ^2 of the BnGa fit as a function of the assumed $N_{3/2^+}(1900)$ mass. The data base includes high-statistics angular distributions, several single (Σ, T and P) and double polarization observables (C_x, C_z, O_x, O_z). A large data base on other reactions is included in the fits. But still, there is not yet a full reconstruction of partial wave amplitude. So the evidence is derived from a χ^2 minimization (see Fig. 4). The best values and errors, $M = 1915 \pm 50$ MeV and $\Gamma = 100 \pm 50$ MeV, cover all solutions with reasonable χ^2.

$\Delta_{3/2^+}(1920)$ and $\Delta_{3/2^-}(1940)$ from $\gamma p \to p\pi^0\eta$:
Fits to this reaction with/without $\Delta_{3/2^+}(1920)$ (left) or $\Delta_{3/2^-}(1940)$ (right) represented by solid lines in Fig. 5 are not not satisfying, both these resonances are needed to achieve a good fit. The fits optimizes for $(M; \Gamma) = (1910 \pm 50; 330 \pm 50)$ $(\Delta_{3/2^+}(1920))$ and $(1985 \pm 30; 390 \pm 50)$ MeV $(\Delta_{3/2^-}(1940))$.
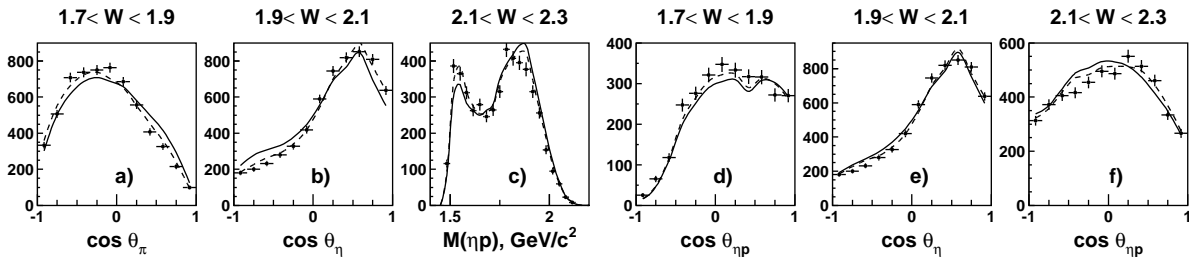

Figure 5: *Selected mass and angular distributions. A fit represented by solid lines without $\Delta_{3/2^+}(1920)$ (left) or $\Delta_{3/2^-}(1940)$ (right) yields a bad fit. Only when both resonances are included (dashed lines), data are reproduced.*

We conclude that **1.** it would be too early to abandon the resonances found in the KH and CM analyses but missed in the GWU analysis, and that **2.** photoproduction begins to make a significant impact on baryon spectroscopy. For the interpretation of the baryon spectrum, all resonances of Table 1 will be used. For further information on the BnGa analysis, see talks by Anisovich and Sarantsev at this conference.

INTERPRETATION

Quark models:

The quark model provides the most natural and most accepted picture of the baryon excitation spectrum. Ingredients are constituent quarks with defined rest masses, a confinement potential (mostly linear) and some residual interaction. In the celebrated Isgur-Karl model and its later "relativized" refinements, an effective one-gluon exchange is chosen as residual interaction. The Bonn group starts from a Bethe-Salpeter equation; the linear confinement potential has a full Dirac structure. Instanton-induced interactions are responsible for the $N - \Delta$ mass splitting. The quark models are very successful in explaining the properties of baryon ground states and low-mass excitations; they fail to reproduce the masses of radial excitations and predict many more baryon resonances than found in experiment.

AdS/QCD:

The Maldacena correspondence relates conformal strongly-coupled theories in space-time to a weakly-coupled ("gravitational") theory in a five dimensional Anti-de Sitter space embedded in six dimensions. Gravitational theories can be solved analytically, the solutions can be mapped into space-time and compared to data. There is a (heuristic) mapping of quantum mechanical operators to operators in Ads/QCD. The fifth dimension in AdS called z can be interpreted as virtuality or distance between constituents. For $z \to 0$, constituents are asymptotically free. Confinement can be enforced by a hard boundary $z < z_{\max} = 1/\Lambda_{QCD}$ (hard wall) or by a soft wall due to a dilation field (or penalty function) increasing as z^2.

AdS/QCD relates masses to the orbital angular momentum L (Fig. 6). In quark models, relativity plays an important role, and only the total angular momentum J is defined. Experimentally, there are a few striking examples where the leading orbital angular momentum and the spin can be identified. To give one example: the four states $\Delta_{1/2^+}(1910), \Delta_{3/2^+}(1920), \Delta_{5/2^+}(1905)$, and $\Delta_{7/2^+}(1950)$ are isolated in mass. They obviously form a spin-quartet of resonances with $L = 2, S = 3/2$. Small admixtures of other components are not excluded.

Figure 6: *One-parameter fit to the Δ excitation spectrum. For nucleon resonances, a term is needed which reduces the mass of baryons with "good diquarks", with a pair of quarks with spin and isospin zero.*
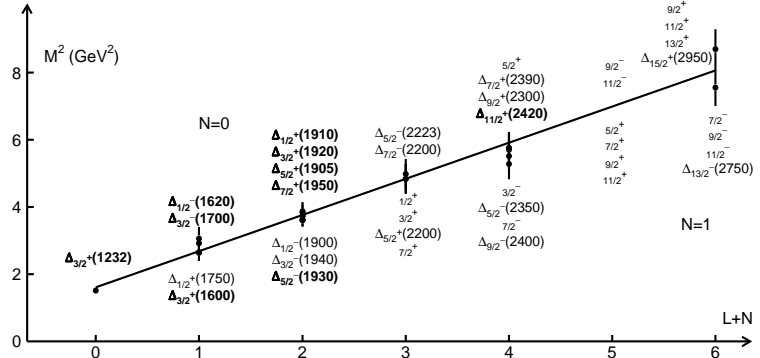
$$\mathbf{M^2 = a \cdot (L + N + 3/2) - b \cdot \alpha_D \left[GeV^2 \right]}$$

$$a = 1.04\, GeV^2 \text{ and } b = 1.46\, GeV^2.$$

Δ resonances have no good diquarks.

Dynamically generated resonances:

The properties of some resonances (and the meson-baryon system at low energies) can be understood very successfully using an effective chiral Lagrangian, relying on an expansion in increasing powers of meson masses and momenta. A problem arises when these dynamically generated resonances are predicted atop the quark-model states, or when the light quark baryons are disregarded altogether and replaced by a systematics of meson–baryon excitations. The pole structure of $N_{1/2^-}(1535)$ and $N_{1/2^-}(1650)$, e.g., was studied by Döring *et al.* [10]. They generated $N_{1/2^-}(1535)$ dynamically and introduced two additional poles, one for $N_{1/2^-}(1650)$ and a third one. The latter pole moves far into the complex plane and provides an almost energy independent background while the dynamically generated $N_{1/2^-}(1535)$ pole appears as a stable object. This could mean that $N_{1/2^-}(1535)$ is fully understood by the interaction of the baryon and meson, into which it disintegrates. It can be interpreted that the observed $N_{1/2^-}(1535)$ is dynamically generated and the state predicted by the quark model is missing. The latter interpretation seems unacceptable to me.

Restoration of chiral symmetry?

In contrary to expectations based on the quark model in harmonic oscillator approximation, the masses of baryon resonances do not increase with alternating states of even and odd parity; often, states having the same J but opposite parities are approximately degenerate in mass (see Table 2). At low mass, $N_{1/2^-}(1535)$ is much heavier than its chiral partner, the proton. In meson spectroscopy, the ρ mass is much below the $a_1(1260)$ mass. The mass difference is assigned to a spontaneous breaking of chiral symmetry. Glozman [11] and others argue that at high-mass excitations, details of the potential responsible for spontaneous chiral breaking are irrelevant: chiral symmetry could be restored in highly excited baryons. The alternative interpretation of the occurrence spin-parity partners, AdS/QCD, is criticized because of the use of orbital angular momentum, a non-relativistic quantity [12], a view contested in [13]. Parity doublets are only observed for resonances on Regge daughter trajectories; mesons and baryons falling on the leading Regge trajectory have no parity partner. This is a challenge for future experiments.

Table 2. *Chiral multiplets (doublets or quartets) of N^* and Δ^* resonances of high mass. List and star rating, see [9].*

$J=\frac{1}{2}$	$N_{1/2^+}(1710)$ ***	$N_{1/2^-}(1650)$ ****	$\Delta_{1/2^+}(1750)$ *	$\Delta_{1/2^-}(1620)$ ****
$J=\frac{3}{2}$	$N_{3/2^+}(1720)$ ****	$N_{3/2^-}(1700)$ ***	$\Delta_{3/2^+}(1600)$ ***	$\Delta_{3/2^-}(1700)$ ****
$J=\frac{5}{2}$	$N_{5/2^+}(1680)$ ****	$N_{5/2^-}(1675)$ ****	no chiral partners	
$J=\frac{1}{2}$	$N_{1/2^+}(1880)$ **	$N_{1/2^-}(1905)$ ****	$\Delta_{1/2^+}(1910)$ ****	$\Delta_{1/2^-}(1900)$ **
$J=\frac{3}{2}$	$N_{3/2^+}(1900)$ *	$N_{3/2^-}(1860)$ **	$\Delta_{3/2^+}(1920)$ ***	$\Delta_{3/2^-}(1940)$ **
$J=\frac{5}{2}$	$N_{5/2^+}(1870)$ **	no ch. partner	$\Delta_{5/2^+}(1905)$ ****	$\Delta_{5/2^-}(1930)$ ***
$J=\frac{7}{2}$	$N_{7/2^+}(1990)$ **	no ch. partner	$\Delta_{7/2^+}(1950)$ ****	no ch. partner
$J=\frac{7}{2}$	no ch. partner	$N_{7/2^-}(2190)$ ****	no ch. partner	$\Delta_{7/2^-}(2200)$ *
$J=\frac{9}{2}$	$N_{9/2^+}(2220)$ ****	$N_{9/2^-}(2250)$ ****	$\Delta_{9/2^+}(2300)$ **	$\Delta_{9/2^-}(2400)$ **

Models versus data:

Model predictions can be confronted with data. The predictions of chiral symmetry restoration give an interpretation of one observation, that baryons often appear as parity doublets. There is no prediction where the masses should be found. For this reason, we do not include this model in the quantitative comparison. Also, models generating resonances dynamically are not suitable for a numerical comparison with data, since only a part of the spectrum is calculated. Well suited are quark models, AdS/QCD, and the Skyrme model (even though this model was left out in the above discussion of models). We use two quark models for the comparison, the relativized quark model of Capstick and Isgur [14] and the relativistic Bonn model [15]. The Skyrme model [16] has two parameters only but predicts less than half the number of the observed states, and the mass predictions are rather inaccurate. The best agreement is achieved with the gravitational model [17], see Table 3. A breakdown of contributions of individual resonances can be found in [18].

The agreement between AdS/QCD and the data is absolutely amazing. Obviously, the two parameters used to describe the data correspond to important physical quantities. The parameter a in front of $L+N$ is related to the maximum distance between constituents, it is related to the size of the baryon. The second parameter b is used to construct an operator in AdS which reduces the size proportional to the diquark fraction with vanishing spin and isospin in the baryon: in this version of AdS/QCD, "good diquark" are smaller in size compared to other diquarks.

The second observation is that the mass depends on the orbital angular momentum L implying that we have a non-relativistic situation. We are used to describe the nucleon as bound state of three constituent quarks each having 1/3 of the nucleon mass. The constituent-quark is generated by chiral symmetry breaking, by the energy of the QCD fields. The quark model assumes that the constituent quark is an object which can be accelerated to relativistic energies; chiral symmetry and chiral symmetry breaking is not effected. This does not need to be the case. Glozman assumes that chiral symmetry is restored. This is the assumption of a central Mexican-hat-like potential where chiral symmetry is dynamically broken at the origin of the hadron. The use of a mean field which leads to a Mexican-hat potential in the rest frame of the nucleon is at least a debateable assumption. The success of AdS/QCD suggests that constituent quarks expand and become more massive when a baryon is excited to high energy. Chiral symmetry is broken in an extended volume, and this might be the reason for the increase in mass.

Table 3. *Comparison of model calculations with the mass spectrum of nucleon and Δ resonances from Table 1.*

Model	Reference	Nr. of parameters	"quality"
Quark model with eff. one-gluon exchange	[14]	7	$(\delta M/M) = 5.6\%$
Quark model with instanton induced forces	[15]	5	$(\delta M/M) = 5.1\%$
Skyrme model:	[16]	2	$(\delta M/M) = 9.1\%$
AdS/QCD model with "good diquarks":	[17]	2	$(\delta M/M) = 2.5\%$

The nucleon is lighter than $\Delta(1232)$, not because of effective-one gluon exchange leading to a magnetic hyperfine splitting but because of the smaller size of the good diquark it contains (which 50% probability). The $\Lambda(1405)$ has such a low mass since it has not only one good diquark but all three pairs have vanishing spin and isospin.

Multiplicity of resonances and the existence glueballs and hybrids:

There is the well-known problem of the *missing resonances*: the number of baryon resonances predicted in quark models exceeds by far the number of observed states. The number of baryon resonances can be counted using harmonic oscillator wave function, with two oscillators ρ and λ. Quark models predict, for given $\vec{L}$ and N, a multitude of states satisfying $\vec{l}_\rho + \vec{l}_\lambda = \vec{L}$ and $n_\rho + n_\lambda = N$. With increasing L and N, the number of predicted states explodes: expected are, e.g. two $N_{1/2^+}$ states in the second shell, seven $N_{1/2^-}$ states in the third shell, ten $N_{1/2^+}$ states in the forth shell. This problem is partly cured in AdS/QCD where at most two $J = 1/2$ states are expected in any shell.

There could be a second problem of too large a number of predicted states. In the quark model, there is e.g. one nucleon resonance with $L = 1$, $S = 1/2$, one state with $L = 1$, $S = 3/2$. The possibility of mixing admitted, we can still identify the $N_{1/2^-}(1535)$ with the predicted $L = 1$, $S = 1/2$ quark model state, and $N_{1/2^-}(1650)$ with $L = 1$, $S = 3/2$. But there is evidence that $N_{1/2^-}(1535)$ can be generated dynamically from $N\eta$-ΛK-ΣK coupled-channel scattering dynamics. Hence there could be a quark model state $N_{1/2^-}(1535)$ and a dynamically generated $N'_{1/2^-}(1535)$. Zou [18] proposes that the observed $N_{1/2^-}(1535)$ has a large $(qqq)(q\bar{q})$ component with all quarks in S-wave. If $N_{1/2^-}(1535) = \alpha|qqq> +\beta|(qqq)(q\bar{q})>$, is there an orthogonal resonance $N''_{1/2^-} = \beta|qqq> -\alpha^*|(qqq)(q\bar{q})>$ and, if so, at which mass? Do hybrid configurations $N'''_{1/2^-} = \alpha'|qqq> +\beta'|(qqq)(G)>$ add to the list of expected resonances? Experimentally, none of these additional states has been observed.

It seems to be worthwhile to stress that the number of bosons is not a well-defined quantity. I propose a view in which the interactions between three (current) quarks provide the primary forces to stabilize a baryon. The three quarks acquire their constituent dynamical mass. Gluons may polarize the vacuum, correlated quark-antiquark pairs are created. Depending on the dynamics, these $q\bar{q}$ pairs may have long-range correlations and may move freely within a hadron as Cooper-pairs or massless Goldstone bosons leading to a fast flavor exchange. Or they may evolve into massive quarks. If their masses approach the mass of "normal" constituent quarks, we rather speak about a nucleon-meson molecule or - invoking color chemistry - about five-quark states. However, the origin of all baryons is the three-quark component. The actual decomposition is a question how the QCD vacuum responds to the primary color source of three quarks at a given mass and with given quantum numbers. The response can be very different, in particular it will depend critically on the presence of close-by thresholds, but it is a unique response. There is no "hidden variable" which decides that three quarks with $L = 1$, $S = 1/2$ will go either into a N, N', N'', or into a N''' configuration, or into different mixtures of these Fock components. There is only one state.

This view has attractive features; it reduces the number of expected but unobserved states. It emphasizes the view that quark-model resonances, dynamically generated resonances, five-quark states are different approaches to understand the same object with its complicated internal structure. The different approaches are all legitimate, none of them carries the truth, and each approach should be tested if the predictions are not in conflict with firm results of other approaches. If the view is extended to the mesonic sector, there are some unfamiliar conclusions. First, the raison d'etre of all scalar mesons is their $q\bar{q}$ component, even of the σ. But this is also a trivial statement: without QCD, there are no nuclear forces. Second, if there is only one scalar isoscalar state (plus radial excitations), with all configurations $q\bar{q}$, $qq\bar{q}\bar{q}$, $q\bar{q}G$, $\pi\pi$, $K\bar{K}$, etc. included, then one further possibility, the GG glueball, is likely also a Fock component in its wave function. In this view, also the GG component does not lead to an extra state, there is no supernumerocity of resonances expected. I am aware of claims that supernumerocity has been proven; the Particle Data Group is strongly biassed into this direction. I maintain that these claims are experimentally not sound, see [20], for a review. Presumably, most scalar isoscalar mesons are realized as flavor singlets or octets. The SU(3) flavor singlets are very wide and form the continuous scalar background, a "narrow" $f_0(1370)$ does not exist. Only the octet mesons have normal hadronic widths; these are $f_0(1500)$, $f_0(1760)$ (which includes $f_0(1710)$, $f_0(1790)$, $f_0(1810)$), and $f_0(2100)$. The flavor decomposition of the low-mass $f_0(980)$ and $f_0(500)$ are strongly influenced by the $\pi\pi$ and $K\bar{K}$ threshold. Scalar mesons have a significant four-quark component but their $q\bar{q}$ component is mandatory: in SU(3), there are nine $q\bar{q}$ states and also nine $qq\bar{q}\bar{q}$ states respecting the Pauli principle. In SU(4), there are 16 $q\bar{q}$ and there could exist 36 $qq\bar{q}\bar{q}$ states, but none of these 20 additional states has been observed.

Interestingly, the view forbids non-exotic hybrids, since they are absorbed into the wave function of $q\bar{q}$ mesons carrying the same quantum numbers. Neither the existence of exotic hybrids is excluded by the arguments given above, nor the existence of pentaquarks in a non-(qqq) configuration.

WHAT IS NEEDED?

It ain't necessarily be so:

The interpretation depends, of course, heavily on the existing data. Hence it is of greatest importance to confirm or refute as many of the states seen in KH and CM and not seen in GWU analyses as possible. Photoproduction experiments start to have a significant impact. Experiments with polarized photon beams and polarized targets have already taken a significant amount of data; results are eagerly waited for. Hyperon photoproduction experiments benefit from the self-analysing power of hyperon decays. Some double polarization variables hit the value 1. This may indicate that a smaller number of observables (and not 8) is already sufficient to constrain the amplitudes fully. At least, the BnGa PWA group noticed that there are much less ambiguities in defining the partial wave amplitudes for hyperon photoproduction when the amplitudes are constrained by $d\sigma/d\Omega$, Σ, P, C_x, C_z, O_x, and O_z. Hence I believe we are at a point where we soon will be able to decide which resonances exist in the mass range below 2 GeV or, perhaps, 2.2 GeV.

Search for missing quark model states:

In the second oscillator shell with $L = 2$, quark models predict states in which the spatial wave function are fully antisymmetric, in which the orbital angular momenta $\vec{l}_\rho$ and $\vec{l}_\lambda$ are both one and couple to $L = 1$. If these states exist, they likely do not decay into $N\pi$ but prefer a cascade where the two oscillators de-excite successively. According to the AdS/QCD mass formula (and its interpretation) one can assume that the mass of this spin doublet $N_{1/2^+}$ and $N_{3/2^+}$ should be between 1.7 and 1.8 GeV. The preferred decay mode could be the cascade $N_{1/2^+} \to N_{1/2^-}(1535)\pi \to N\eta\pi$ or $N_{3/2^+} \to N_{3/2^-}(1520)\pi \to N\pi\pi$ where all decays proceed via S-wave.

What is the mass of the first $\Delta_{7/2^-}$ resonance?

We have already mentioned the quartet of states $\Delta_{1/2^+}(1910)$, $\Delta_{3/2^+}(1920)$, $\Delta_{5/2^+}(1905)$, and $\Delta_{7/2^+}(1950)$. The first three states have spin-parity partners $\Delta_{1/2^-}(1900)$, $\Delta_{3/2^-}(1940)$, $\Delta_{5/2^-}(1930)$. In quark models, the masses of positive parity states are well reproduced, those of the negative-parity states are unexpectedly low. In AdS/QCD, the positive-parity states have $L = 2, N = 0$, the negative-parity states $L = 1, N = 1$, respectively, and are predicted to be degenerate in mass. Since $\vec{L} + \vec{S}$ yields only $J = 1/2^-$, $J = 3/2^-$, and $J = 5/2^-$ negative-parity states, but $J = 1/2^+, \cdots J = 7/2^+$ for $L = 2, S = 3/2$, the absence of a parity partner of $\Delta_{7/2^+}(1950)$ is expected. Instead, 2184 MeV is predicted as $\Delta_{7/2^-}$ mass, close to the PDG resonance $\Delta_{7/2^-}(2200)$.

If chiral symmetry were restored in high-mass baryons, the $\Delta_{7/2^-}$ mass would need to be degenerate in mass with $\Delta_{7/2^+}(1950)$. The mass is 2200 MeV, hence we could conclude that AdS/QCD is favored. However, the $\Delta_{7/2^-}(2200)$ mass determination is not very reliable. In Table 4 we list the Particle Data group entries for $\Delta_{7/2^-}(2200)$. The values a very consistent but the resonance is given one-star only. In the GWU analysis [4], the state is not seen. This is certainly not the level of confidence we need in order to settle the question if chiral symmetry is restored or broken in high-mass hadron resonances.

Table 4: *PDG entries for $\Delta_{7/2^-}(2200)$.*

Mass [MeV]	Width[MeV]	Ref.
2200±80	450±100	[2]
2215±60	400±100	[3]
2280±80	400±150	[21]

Spin-parity doublets are also observed in the meson spectrum, for many mesons but not for those on the leading Regge trajectory. To give an example: there is a $a_4(2040)$ meson with $J^{PC} = 4^{++}$ but the lowest mass partner with $J^{PC} = 4^{-+}$ is $\pi_4(2250)$, and the same observation can be made for the lowest-mass states in the series $J^{PC} = 1^{--}$, $J^{PC} = 2^{++}$, $J^{PC} = 3^{--}$, $\cdots$. Hence spin-parity partners are missing for the most important states. The following argument by Glozman [22] suggests a dynamical reason why the postulated $J^{PC} = 4^{-+}$ state at 2040 MeV was not observed: mesons in the high-mass region stem mostly from the QMC-St-Petersburg analysis of Crystal-Barrel LEAR data on $\bar{p}p$ annihilation in flight. And the $\bar{p}p$ system couples to $J^{PC} = 4^{++}$ with $L = 4$ while for formation of a $J^{PC} = 4^{-+}$ state, $L = 5$ is required. Hence $\pi_4(2250)$ could be suppressed. It is worthwhile to note that the observed pattern is is expected in AdS/QCD. Mesons – except scalar and pseudoscalar mesons – are well described by the formula in the caption of Fig. 6, if the "3/2" is replaced by "1/2".

In photoproduction or pion-induced reactions, there is no such angular momentum suppression; hence the search for the lowest-mass $\Delta_{7/2^-}$ resonance seems to be the most rewarding case to decide if quark models or AdS/QCD describe best the mass spectrum, or if chiral symmetry is restored at high excitation energies.

Limits of dynamical generated resonances:

The range of applicability of the method to generate resonances dynamically has to be understood. As experimen-

talist, I am ready to believe that $N_{1/2^-}(1535)$ can be generated dynamically from its decay products, also that it could have, at large distances, a sizable five-quark or molecular component in its Fock-space expansion. But it is difficult to accept that $N_{1/2^-}(1535)$ and $N_{3/2^-}(1520)$ are fundamentally different objects. Oset in his contribution to this conference [23] constructed scalar and tensor mesons from vector-vector interactions. The isoscalar scalar mesons are found at 1512 MeV and 1726 MeV. This looks like a success as well as the tensor meson found at 1275 MeV. However, the next tensor at 1525 couples with similar strength to $K^*\overline{K}^*$, $\omega\omega$, $\phi\omega$, $\phi\phi$, but not to $\rho\rho$. This is in striking conflict with what we know about $f_2(1525)$: it is a $s\bar{s}$ state, the tensor mesons have a mixing angle close to the ideal one. OZI rule violating couplings like the one into $\phi\omega$ are highly suppressed. Also the isovector states are a failure. If $\rho\rho$ generates $f_2(1270)$, $\rho\omega$ must generate $a_2(1320)$; the predicted lowest isoscalar tensor mass is 1567 MeV and its scalar companion is predicted to have 1777 MeV. In my view, it is important to find out the conditions for a meaningful unitarization of chiral amplitudes, and not to enjoy the achievements and to neglect the failures.

Excited states on the lattice:

Lattice gauge calculation have entered the difficult task to explore the spectrum of baryon resonances and to address their finite width. In the Introduction, I showed how the mass of a quark evolves with decreasing momentum transfer. The calculation was done for a quark propagator irrespective of its environment. According to the discussion above, the constituent quark mass should depend on its neighborhood; it should be lighter in the nucleon than in the $\Delta(1232)$, and massive in highly excited states.

CONCLUSIONS

Baryons have played a very important role in the development of particle physics, starting from the - at that time - mysterious proton and neutron magnetic moments, the discovery of the $\Delta(1232)$ by Fermi and his collaborators, to the discovery of SU(3) and the insight that quarks need an extra degree of freedom which is now known as color. The concept of chiral symmetry and chiral symmetry breaking is at the root of modern strong interaction physics. With the new tools, in experiment and theory, we have the chance for a new understanding of strong interaction dynamics in the confinement region.

REFERENCES

1. C. Amsler *et al.* [Particle Data Group], Phys. Lett. B **667**, 1 (2008).
2. G. Höhler, F. Kaiser, R. Koch and E. Pietarinen, "Handbook of Pion Nucleon Scattering," Physics Data, No.12-1 (1979).
3. R. E. Cutkosky *et al.*,"πN Partial Wave Analysis," 4th Int. Conf. on Baryon Resonances, Toronto, Canada, 1980.
4. R. A. Arndt, W. J. Briscoe, I. I. Strakovsky and R. L. Workman, Phys. Rev. C **74**, 045205 (2006).
5. P. O. Bowman *et al.*, Phys. Rev. D **71**, 054507 (2005).
6. A. Chodos, R. L. Jaffe, K. Johnson and C. B. Thorn, Phys. Rev. D **10**, 2599 (1974).
7. M. S. Bhagwat, M. A. Pichowsky, C. D. Roberts and P. C. Tandy, Phys. Rev. C **68**, 015203 (2003).
8. D. Diakonov and V. Y. Petrov, Sov. Phys. JETP **62**, 204 (1985) [Zh. Eksp. Teor. Fiz. **89**, 361 (1985)].
9. E. Klempt and J. M. Richard, arXiv:0901.2055 [hep-ph].
10. M. Döring and K. Nakayama, arXiv:0906.2949 [nucl-th].
11. L. Y. Glozman, Phys. Rept. **444**, 1 (2007).
12. L. Y. Glozman, arXiv:0903.3923 [hep-ph].
13. G. F. de Teramond and S. J. Brodsky, arXiv:0903.4922 [hep-ph].
14. S. Capstick and N. Isgur, Phys. Rev. D **34**, 2809 (1986).
15. U. Löring, B. C. Metsch and H. R. Petry, Eur. Phys. J. A **10**, 395 (2001).
16. M. P. Mattis and M. Karliner, Phys. Rev. D **31**, 2833 (1985).
17. H. Forkel and E. Klempt, Phys. Lett. B **679**, 77 (2009).
18. E. Klempt, Nucleon excitations, QNP2009, arXiv:1001.2997v1 [hep-ph].
19. B.S. Zou, "Evidence for a new Σ^* resonance with $J^P = 1/2^-$ around 1380 MeV ", contr. 62.
20. E. Klempt and A. Zaitsev, Phys. Rept. **454**, 1 (2007).
21. A. W. Hendry, Phys. Rev. Lett. **41**, 222 (1978).
22. L. Y. Glozman, arXiv:0912.1129 [hep-ph].
23. E. Oset, "The $f_0(1370)$, $f_0(1710)$, $f_2(1270)$, $f_2'(1525)$ and $K_2^*(1430)$ in a unitary approach", contr. 51.